

Glacial and karst landscapes of the Gort lowlands and Burren.

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Introduction

The Burren Hills

The Burren is one of the most striking and distinctive landscapes in the whole of Ireland, a vast undulating and terraced upland of often bare or thinly vegetated Carboniferous limestone rising often steeply from the coast to an altitude of more than 300 metres in places. In an Ireland-wide context, however, the Burren represents an intriguing anomaly. Some 40% of Ireland is underlain by Carboniferous limestones often barely distinguishable from those of the Burren yet over almost their entire outcrop these mechanically tough limestones seldom rise significantly above 50 metres O.D. Indeed, the eastern edge of the Burren plateau ends abruptly at a steep scarp overlooking the Gort lowlands, again developed on virtually identical limestones, which here seldom rise more than 30 metres above sea level.

The reason that the limestone outcrop across Ireland is predominantly lowland arises from its solubility compared with other rock types. Limestone is removed in solution, a relatively low energy process that is not dependent on water flow velocity. In contrast, other rock types with very much lower solubilities are removed largely by erosion, a relatively high energy process that occurs only when water flow is faster than about 0.2 m/s even for the smallest and most loosely packed sediment particles. Water percolating slowly through these relatively insoluble rocks will alter their composition and mechanical properties through weathering, but it cannot move the particles themselves until a threshold flow velocity is exceeded. Hence erosion is dependent on occasional high-energy flood events whereas dissolution of limestone is much more continuous. In the prevailing climate of Ireland, with endless ‘soft days’ punctuated by only occasional downpours, dissolution of limestone and weathering of other rock types is favoured much more than erosion. As a result, over time scales of millions of years limestone outcrops across Ireland have been lowered at a faster rate than outcrops of other rock types, in a kind of denudational ‘Tortoise and Hare race’ (Simms, 2004). The Burren limestone owes its survival as uplands to a protective cover of mudstones and sandstones which was stripped away only relatively recently. In contrast the shale cover over what is now the Gort lowlands was eroded away millions of years earlier, exposing the limestone beneath to prolonged dissolution.

Through much of the Cenozoic Ireland’s climate probably has been largely humid temperate, accounting for the overall topographic contrast between limestone and other rock types. Subsequent repeated glaciations through the Pleistocene had a profound influence on the topography of Ireland.



Figure 1.1. Typical glaciokarst landscape of thinly vegetated limestone pavement near Mullagh More, in the south-east Burren. The height of the pedestal beneath the erratic boulder on the right provides a rough measure of surface lowering of the surrounding pavement since the last ice retreat.

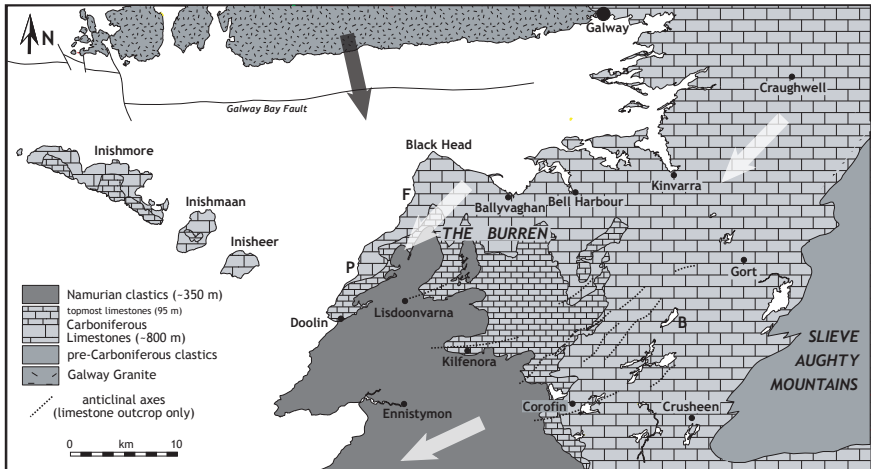


Figure 1.2. Simplified geological map of the Burren, Gort lowlands and Galway Bay area showing the distribution of the main rocks types referred to in the text, and the direction of the penultimate (dark grey arrow) and final (pale arrows) glacial advances across the region (after MacDermot et al., 2003, and Simms, 2000). B=Lough Bunny; F=Fanore; P=Poulsallagh.

The Carboniferous limestones of the Burren are mechanically strong and relatively resistant to glacial erosion. Traversed by a series of conspicuous joints, the dominant set of which is orientated almost north-south, and generally quite massively bedded, only in the upper part of the succession are thick limestones separated by thin (<1 metre) clay wayboards (Simms 2003a). Ice movement during the Pleistocene rounded and smoothed the northern flanks of the limestone hills while on their southern, down-flow sides large masses of limestone became separated along prominent joints and rafted along the clay wayboards or broken up, creating the distinctive crags and terraces of the Burren. In contrast to the mechanically strong limestone, the overlying mudstones and sandstones, which may already have experienced deep weathering, were more susceptible to glacial erosion, glaciotectonism along bedding planes, and to periglacial freeze-thaw and gelifluction.

It seems likely that throughout much of the Neogene the exposed limestones of the Gort lowlands and much of the Irish midlands were slowly and continuously being removed by dissolution. At the same time the limestone that now forms the Burren uplands was protected from this solutional denudation by a more slowly eroding, but increasingly deeply weathered, cover of mudstones and sandstones. The onset of the Pleistocene glaciations saw the weathered mudstones and sandstones preferentially stripped away to expose an upland plateau of mechanically tough limestones. Estimated surface lowering rates of the limestone of the order of 30-50 mm/ka, coupled with extensive outcrops across the plateau of the Slevenaglasha Formation at the top of the limestone succession, suggest that the upland areas of the Burren, and the Aran Islands offshore to the west, remained shale-capped into the latter part of the Pleistocene. The abrupt scarps to the east, overlooking the Gort lowlands, and to the north and west, looking out across Galway Bay and continuing north-westwards along the Aran Islands, probably approximate to the position of the shale edge early in the Pleistocene, at which time Galway Bay would have formed an extension of the Gort lowlands. Nonetheless, this early Pleistocene shale-capped massif was breached by various major topographic features which penetrated through into the limestone beneath. The largest of these still survive today as the Ballyvaghan and Turlough valleys descending to the north, and the major enclosed depressions, or uvalas, of Carran, Meggagh and Kilcorney (Simms, 2003b).

Once unroofed, the limestones of the Burren uplands have been subjected to the same dissolutorial processes as originally created the extensive lowlands further east, with the development of a range of characteristic karst features such as dolines, pavements and caves. The time elapsed since the retreat of the last ice sheet, ~15 ka, has allowed only relatively limited development of karst landforms such that the distinctive landscape of bare rock pavements and crags is termed glaciokarst, encompassing characteristics of both glacial and karst processes. In general the upland limestones are more deeply dissected by karst features in the

north-east of the Burren than further to the south-west, suggesting a progressive unroofing of the limestone from north-east to south-west. Indeed a shale cap still persists today on Poulacapple and Slieve Elva in the south-west Burren. One line of evidence indicating this rapid unroofing of the limestone comes from the distribution of cave systems within the Burren. Most of the known caves, both active and fossil, are located close to the present shale margins of Poulacapple and Slieve Elva. A slow retreat of the shale edge southwestwards across the Burren might be expected to leave remnants of similar swallet caves, marking previous positions of the shale edge, at other points on the Burren plateau yet, despite the exceptional exposure of limestone afforded by the crags and terraces across the high Burren, remarkably few caves have been found there. Destruction of shallow cave passages by glacial erosion is one factor to consider while rapid retreat of the shale cover may have prevented the development of all but shallow and immature cave systems during relatively brief pauses in the position of the shale edge (Simms, 2003b).

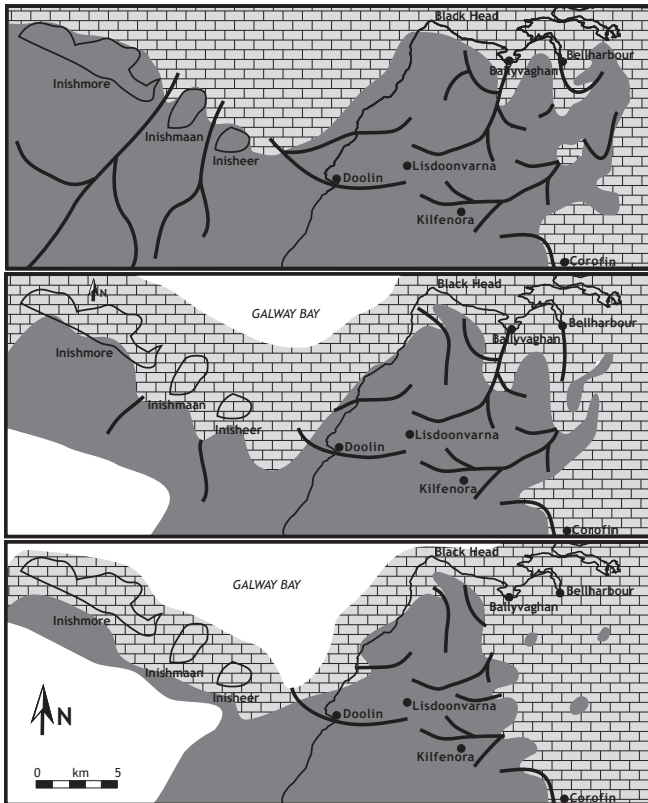


Figure 1.3. Hypothesised pattern of removal of the shale cover across the limestone of the Burren and Aran Islands from the late Neogene to the mid-Pleistocene.



Figure 1.4. The glacially rounded northern scarp of the Burren hills, looking eastwards across Gleninagh Mountain, and drowned lowlands of Galway Bay. The overlying shale cover probably extended to the scarp edge until well into the Pleistocene.



Figure 1.5. Glacially striated limestone, with striae oriented northeast-southwest, overlain by limestone-rich till on the coast at Poulcraven, between Doolin and Poulisallagh.

There is abundant evidence that at least the last two glacial advances across the region came broadly from the north. North-facing scarps, such as that west of Ballyvaghan, were smoothed and rounded by ice sheets moving south. In contrast south-facing scarps, such as those of Oughtdarra, north-west of Lisdoonvarna, were plucked or had huge limestone blocks shunted along shale beds to create jagged crags and chaotic jumbles of limestone debris. Glacial striae, formed by the last advance, have a predominantly north-east to south-west orientation. Most glacial erratics are demonstrably local in origin, of limestone or Namurian sandstone and hence consistent with this direction of ice movement. However, occasional more exotic clasts were derived from outcrops of granite, schist or quartzite to the north of Galway Bay and suggest another ice advance more directly from the north or even north-west.

The Gort Lowlands

Despite its almost unremitting low altitude, the Gort lowlands form a far from monotonous landscape. Occupying a strip of low ground, mostly 15-20 km wide, it stretches from the foot of the Burren hills, here rising abruptly to some 250 metres, eastwards to the foot of the Slieve Aughty hills, an unroofed inlier of Devonian and older sandstones and mudstones rising in places to around 400 metres. Its southern and northern limits are more arbitrarily defined, perhaps extending to Craughwell in the north and Crusheen in the south. Within this area several distinct, but related, landscapes can be recognised (Drew 2001, 2003). East of Gort various streams drain from the impermeable catchment of the Slieve Aughty hills and sink soon after passing on to the limestone. Thereafter much of the drainage is underground (Drew, 2004; Simms, 2001). The area for a few km north and west of Crusheen is characterised by numerous lakes, such as Lough Bunny (R 380968), 7 km south-west of Gort. Occupying shallow limestone basins, and with water levels mostly at around 17 metres O.D., these are 'water-table' lakes fed largely by springs and draining via swallets. For a few kilometres to the north and west of Gort excess flow from the sinking streams to the east, and some of the water table lakes to the south, re-emerges at ephemeral lakes, or turloughs, following heavy rain. Subsequent drainage of this ponded water is focussed on the perennial lake of Coole Lough (M430040), where a large swallet on its west side connects with a major conduit below. This conduit drains to major coastal springs at Corranroo (M 324105) and Kinvarra (M 381105), en route passing beneath an extensive area of bare limestone pavement which permanently lacks any significant surface water. Remarkably some of the lakes which are located along the route of this conduit, such as Caherglassaun Lough (M 415063), respond to tides on the coast despite their location several km inland.

The lowland karst landscape across this region, and the major karst drainage system beneath, owe their existence to processes that were operating for several million years before the Pleistocene but were significantly affected by subsequent

glaciations. Drumlins are common towards the eastern side of the lowlands while erratic boulders, mostly of local limestone but occasionally of Galway granite, are a conspicuous feature of the monotonous glaciokarst limestone pavements to the south and west of Kinvarra. Another effect of Pleistocene glaciation has been the disruption of the underground drainage and destruction of shallower sections. Only the deeper conduits, such as between The Punchbowl (M 455002) and Cannahowna Cave (M 445003), and between Caherglassaun Lough and the coastal risings, have survived largely intact despite the effects of glacial erosion and dissolutional surface lowering. Elsewhere shallow sections have been truncated or choked with sediment, leading to the development of the unique turloughs of this area.

Site 1.1. Newtown Turlough

(Parking grid reference M 427022)

One of several turloughs to the west of Gort, Newtown Turlough (M 427022) is perhaps the easiest to view and to appreciate the scale of flooding which can occur. An artificial causeway, New Line, some 5 metres high traverses the southern side of the turlough before passing onto an extensive raised area of rough limestone pavement. In late summer the turlough usually is reduced to an extensive shallow grassy basin, often grazed by cattle, with only a few scattered pools fed by sluggish streams. Following prolonged wet weather water pours from various points in the floor and flanks of the basin and may fill the basin to a depth of several metres in only a few days (Simms, 2001) subsequently draining, often via the same openings (estavelles) over the course of a few weeks. In the exceptional floods of 1995 (MacDermot, 1995) the causeway itself was submerged by nearly 2 metres and several of the turloughs merged into a single vast body of water, with a surface river some 50 metres wide flowing westwards to Caherglassaun Lough.

Site 1.2. Kilmacduagh

(Parking grid reference M 406002)

Kilmacduagh is one of the most important and best preserved, and also one of the most infrequently visited, of Ireland's ecclesiastical sites. It derives its name from a monastery founded here in the 7th Century by St Colman, son of Duagh, a member of one of the local royal families. The site is dominated by the 112 foot (34.5 m) round tower which leans 2 feet (0.6 m) out of true. A slight change of slope of the south flank about 20 metres up indicates that remedial measures were necessary to correct this lean which, as in its more spectacular analogue in Pisa, clearly had begun before building was complete. On the north side of the tower near its base an intriguing vertical furrow, ~2-3 cm deep, beneath a small hole appears to have developed through rainwater draining from the tower. If this notch has formed entirely since the tower was built some 1000 years ago then it provides a measure of the dissolution rate due to rainwater runoff and is broadly comparable with rates estimated from pedestal heights beneath erratics on the Burren (Drew in



Figure 1.1.1. Newtown Turlough, as viewed from New Line, during dry weather (A) and following Autumn floods (B).

Warren and O'Connell, 1993). Adjacent to the tower is the Cathedral, with various parts dating from the 11th to 15th Century. Remains of at least three churches, dating from the 12th to 15th Century lie a short distance across fields to the north and north-west with another, built around 1200, across the road to the east. A two-storey building just west of the road is possibly the Abbot's house, built in the 13th Century but much altered since. Most of the impressive array of gravestones which now surround the cathedral and round tower date from the 19th and 20th centuries.

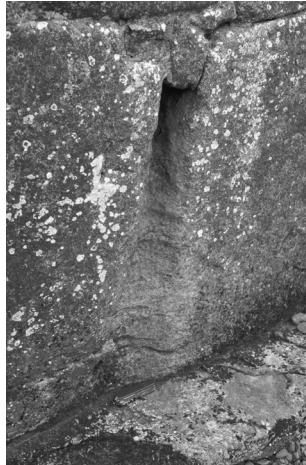
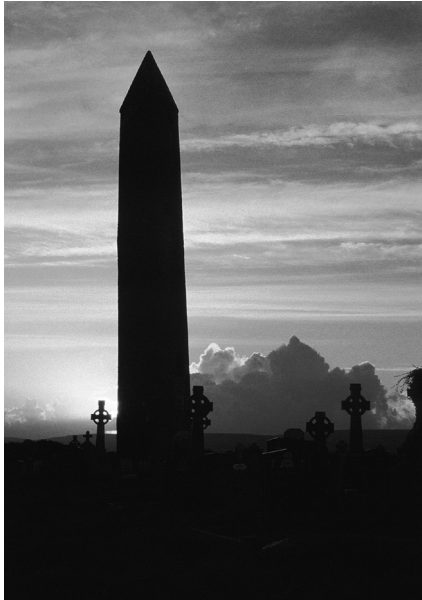


Figure 1.2.1. The leaning round tower at Kilmacduagh and the dissolutional notch at the base of Kilmacduagh round tower. Penknife is 90 mm long.

Site 1.3. Lough Bunny

(Parking grid reference R 380968)

Lough Bunny is a shallow elongate lake basin located about 8 km to the south-west of the town of Gort, Co. Galway, and immediately north of the Gort-Corofin road (R460). The area in general is dominated by a gently undulating expanse of sparsely vegetated limestone pavement interspersed with scattered patches of more richly vegetated glacial till and low drumlins. The lake has a length of about 2 km and maximum width of about 600 metres, with its long axis orientated roughly NE-SW, subparallel to the prevailing ice direction during the most recent glacial advance. Limestone is extensively exposed around the northern end of the lake; the western shore is indented, craggy in places, and fronted by several small rocky islands, but the eastern shore is almost straight and, over much of its length, almost parallel with the regional strike of the limestone, which varies

only slightly between about 030° and 040° with a dip to the north-west at about 8°. Consequently long stretches of the eastern shore are formed on individual bedding surfaces. The limestone is cut by two major joint sets which, being orientated just east of north (012°) and east-west (090°), are oblique to the eastern lake margin. A third minor joint set is orientated roughly parallel to strike and hence parallel to the lake margin. The surface of the lake lies at about 17 metres O.D., corresponding within a metre or two to many of the other lakes in this lowland karst region and suggesting that it lies very close to the regional karst piezometric surface (water table). Drew and Daly (1993) considered Lough Bunny to represent the overflow of an important underground flow route connected with the regional Coole-Kinvarra karst drainage system. No significant surface streams either enter or leave the lake but during periods of high rainfall it is fed by many small springs, principally along its eastern shore, with the outflow being via a series of sinks along the north-west margin of the lake.

The lake is highly oligotrophic with the water in a near permanent state of carbonate saturation. There is extensive precipitation of carbonate marl from the lake water, probably enhanced by uptake of CO₂ by aquatic plants, and marl crusts are visible on limestone exposed when water levels are low. In this ‘encrusted zone’ the joints remain tight and the limestone surfaces are devoid of any karst dissolutional features. However, passing up the shore the initially smooth limestone surface shows a progressive widening of joints and development of ‘eggbox pitting’, small subcircular solution pits characteristic of lacustrine environments (see description of the Lough Mask shore), ultimately passing into irregular limestone pavement

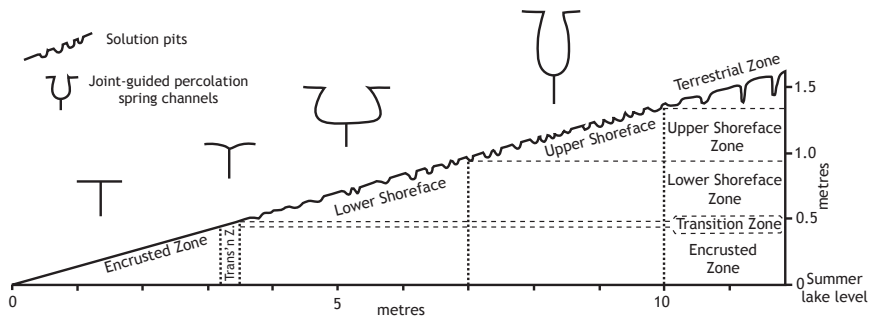


Figure 1.3.1. Diagrammatic sketch section across the eastern shore of Lough Bunny showing the relationship of karren development to seasonal water levels.

typical of subaerial environments. This sequence appears to reflect the interaction between precipitation of carbonate onto the submerged limestone by the lake water and dissolution by rainwater and percolation water emerging from joints along the shoreline when water levels fall. On the lower shore there is no dissolution of the limestone by the saturated lake water when water levels are high and when

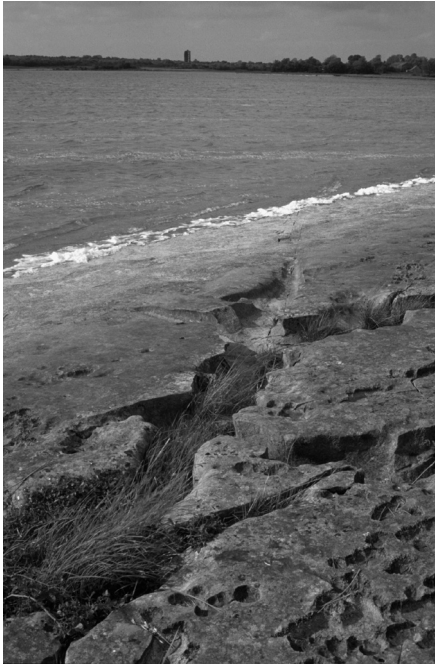


Figure 1.3.2. Percolation spring channels, ‘eggbox pitting’ and, closer to the lake edge, the unkarstified ‘encrusted zone’ exposed on the eastern shore of Lough Bunny, Summer 2004.

water levels are low for a few weeks or months in the summer the newly exposed limestone is buffered from significant rainwater dissolution by a carbonate marl crust. Moving higher on the shore the length of time the limestone is subject to marl precipitation decreases while its exposure to dissolution by rainwater and/or emerging percolation water is correspondingly increased. Water emerging along joints has created many deep U-shaped channels oblique to the lake edge, often associated with shallower channels where water has overflowed directly down-dip. The ‘eggbox’ solutional pits are somewhat enigmatic, being characteristic of the margins of even strongly saturated lakes. Their location high on the shore suggests their formation may be related to dissolution by slightly undersaturated water left behind after larger floods, perhaps with some component of mixing solution from rainwater. Research at this site is ongoing but it demonstrates the range of karst dissolution rates which have occurred through the Holocene in this region of Ireland.

Lough Inchiquin, Clifden Hill and Kilnaboy mushroom stones

The geomorphology of the area around Corofin provides a possible analogue for an earlier stage in the development of the Burren hills further to the north, before the shale cover there was stripped away. The town is located on limestone lowlands, barely rising above 20 metres O.D., dotted with lakes such as Lough Inchiquin to the northwest and Lough Atedaun immediately to the east.

Immediately west of Lough Inchiquin a steep scarp rises more than 150 metres above the lake. The top of the limestone here lies at about 70 metres O.D., more than 50 metres higher than the present lake surface, suggesting that while the limestone lowlands to the east have been exposed to surface lowering for perhaps a million years, the limestone to the west has been protected from dissolution by several tens of metres of overlying shale.

The lake basins around Corofin form part of a complex hydrological



Figure 1.3.3. ‘Mushroom Stones’ to the east of the road at Kilinaboy; wave-notched limestone boulders marking the former extent of Lough Inchiquin.

system involving both surface and underground drainage. The main feeder to Lough Inchiquin is the headwaters of the River Fergus, deriving most of its flow from a series of large springs which account for some 40% of the total drainage from the Burren uplands to the north (Drew, 2003). Downstream of Lough Inchiquin the Fergus River follows a tortuous route via a series of lake basins, surface rivers and underground channels. Artificial channels now connect originally discontinuous stretches of the surface drainage and, in some cases, significantly lowered the level of some of the lakes to create often broad marshy flats. The former extent of some of these lakes, notably Lough Inchiquin itself, is evident from the presence of conspicuously notched limestone boulders, often called mushroom rocks or wave stones (Dunne and Feehan, 2001), marking former lake levels. Particularly fine examples of these can be seen on the east side of the main Ennis–Corofin–Kilfenora road (R476) at several points, notably a little south of Corofin (R 287885) and to the north at Kilinaboy (R 273914).

Site 1.4. Poulsallagh

(Starting point grid reference M 087020)

The small bay of Poulsallagh and the area around it is one of the most fascinating, informative and accessible sites in the Burren, encompassing a wealth of karst, coastal and glacial features within a few minutes walk of the coast road. In a broader setting Poulsallagh lies on the coast at the south-western corner of the Burren, less than 2 km from the shale edge to the south-east and from the imposing crags of Oughtdarra, and the shale outlier of Slieve Elva and Knockauns Mountain to the east-north-east. Warren (in Warren and O'Connell, 1993) noted an abundance in this area of very coarse boulder till scattered in rough heaps subparallel, or sometimes at right angles, to the prevailing ice direction; the latter were compared with similar transverse ridges in drumlinised areas of Co. Mayo and perhaps represent Rogen moraines.

Poulsallagh Bay itself, barely 150 metres wide and occupied by an impressive storm beach, is one of only a handful of small bays along the rocky western coast of the Burren. Its north and south flanks show, in microcosm, the general topographic effects of prevailing ice movement from the north during at least the latter part of the Pleistocene. The north flank of the bay has a stepped profile, where limestone blocks have been plucked and/or shunted along bedding planes by ice moving from the north, while the south flank has a smoothly rounded profile in places draped by pale grey, limestone-rich till. Glacial striations with a north-east to south-west orientation are conspicuous on this rounded surface, particularly where the till has been recently stripped by marine erosion. These glacial modifications demonstrate that the bay itself predates at least the last glacial advance. It appears to represent the seaward end of a shallow valley perhaps linked with the Coolagh Valley at the southern end of Slieve Elva (Simms, 2003b), although much of the valley for about a kilometre inland from Poulsallagh lies buried beneath vast mounds of glacial debris extending south from Oughtdarra.

Site 1.4a. North of Poulsallagh Bay

(Starting point grid reference M 087023)

Excellent examples of typical limestone pavement extend for several hundred metres north of Poulsallagh Bay and demonstrate many typical features in addition to the ubiquitous clints and grikes.

1. Kamenitzas or solution pans:

Shallow solution pans, or kamenitzas, typically a few cm deep and a few to several tens of cm across, are formed by ponded rain water on the flat surfaces of some of the larger clints. A noticeable feature of many, and that has long aroused curiosity, is the presence of irregular, often sharp-edged, raised rims around these solution pans. These rims, which may rise up to 2 cm above the surrounding limestone surface, are not due to any obvious lithological differences in the

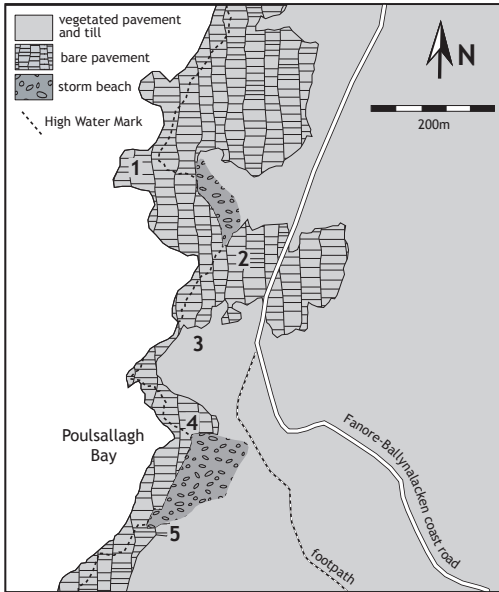


Figure 1.4.1. Sketch map of the area around Poulsallagh Bay, with the location of features of interest indicated.

- 1 - Typical intertidal karren; the type locality of Lundberg (1977).**
- 2 - typical limestone pavement with kamenitzas and boulders on pedestals.**
- 3 - Pol na Grianloch (Quartz Pebble Cave).**
- 4 - Poulsallagh Cave.**
- 5 - Fissure containing two distinct diamicts and truncated by glacially striated surface capped by limestone-rich till.**

limestone, but instead correspond to the splash zone that forms around each solution pan on windy days. Water within the solution pans dissolves some of the limestone which is then reprecipitated as the splashed water evaporates. Subsequent rainfall must then redissolve this precipitated carbonate before it can begin to dissolve the limestone beneath and consequently the limestone beneath the splash zone will be lowered at a slower rate than either the solution pan or the surrounding limestone.

2. Boulders on pedestals:

Numerous erratic boulders of limestone, left behind by the last ice sheet, lie scattered across the limestone pavements of the Burren. Several examples to the north of Poulsallagh Bay lie perched on low pedestals rising above the general surface of the surrounding limestone pavement. These erratic boulders have sheltered the limestone immediately beneath from dissolution by rain, somewhat in the manner of a stone umbrella, and hence their heights are important as providing a rough measure of denudational lowering of exposed limestone surfaces across the Burren. Drew (in Warren and O'Connell, 1993) found the mean pedestal height beneath 78 erratics in the north-western Burren to be 350 mm indicating a surface lowering rate of ~ 35 mm/ka if this occurred in the last 10,000 years.

3. Littoral karst:

Between high and low water a distinctive suite of karst features are developed on exposed limestone on the shore. Elements of this littoral karren



Figure 1.4.2. Typical solution pans, with raised rims on the limestone pavement at Poulsallagh.

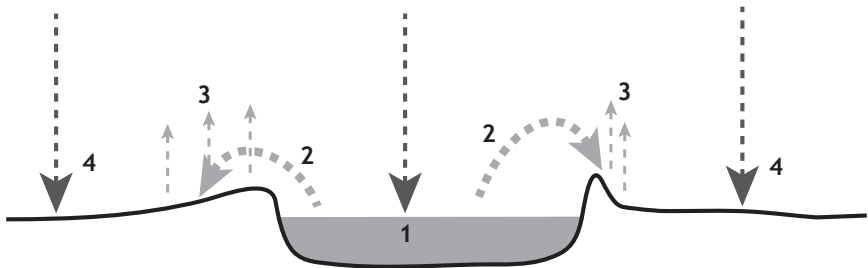


Figure 1.4.3. Mechanism of formation of the raised rims seen around many solution pans on the Burren. 1 – rainwater ponds in small depression, dissolving limestone; 2 – water, with its dissolved limestone, splashes area around pan; 3 – splashed water film evaporates to leave thin film of carbonate over limestone; 4 – dissolution of limestone by rainwater is buffered by carbonate film, hence surface in splash zone is lowered more slowly than surrounding limestone. Asymmetry of the rims appears to be related to prevailing wind direction in many examples.

assemblage persist above high water and there is a gradual transition upwards and landwards into fully terrestrial karst features. The first detailed accounts of temperate littoral karren were based on observations made at this site (Lundberg, 1977; Drew, 2001). Lundberg (1977) recognised four distinct morphological zones; a Mussel-echinoid Zone towards low water, a Barnacle Zone extending up to mean high water, a Periwinkle (*Littorina*) Zone, and a Lichen (*Verrucaria*) Zone extending above high water mark. Characteristic of each are pools, pinnacles and often sharply fretted limestone surfaces which have a morphology quite distinct from limestone surfaces found in the terrestrial zone, and which have elicited much discussion as to their formation. Sea water in general is too saturated with carbonate for significant dissolution to occur directly, but bioerosion by a range of macroscopic and microscopic animals, and by endolithic algae, is recognised as a significant component of this process. Lundberg (1977) and others also suggested that respiration of animals and algae in rock pools may increase the aggressivity of sea water during the hours of darkness, when photosynthesis does not occur to remove respired carbon dioxide, and hence there may be some direct dissolution. However, observations that marine littoral karren are entirely absent from the darkest regions of partly drowned caves (such as Poulsallagh Cave described below) along the Burren coast suggest instead that the development of littoral karren may be due almost entirely to bioerosion (Simms, 1990). In dimly lit areas of these drowned caves only unidirectional pinnacles, or photokarren, are developed, indicating that the presence of light is crucial to the development of marine littoral karren and suggesting that photosynthetic endolithic algae are a fundamental component.

4. *Poulsallagh Cave:*

A 39 metre long meandering section of cave passage is present on the north side of Poulsallagh Bay and, for the more adventurous, can be followed northwards past two openings in the roof to a blockage. The cave passage has a narrow canyon-like section similar to that seen in many of the currently active swallet caves found around the shale outliers of Poulacapple and Slieve Elva. These swallet caves lie within the vadose zone (above the water table) and their narrow canyon-like shape reflects downcutting of the passage floor by the stream. However, despite its superficially similar shape, Poulsallagh Cave did not form in this way. Even in the unroofed seaward section of passage, and still more clearly a few metres into the roofed section of the cave, the passage walls display conspicuous undulating ledges and notches. These undulating ledges are characteristic of paragenetic cave passages that formed in the phreatic zone (below the water table) and mark the former position of undulating sediment deposits on the passage floor. The sediment protected the lower part of the passage from dissolution, which instead was focussed in the upper part of the passage. Over time the passage roof rose as more sediment was deposited on the floor, creating a narrow canyon-like passage largely filled with sediment. Here at Poulsallagh the sediment has been flushed out by marine

erosion revealing the sequence of paragenetic notches on the passage walls. Poulisallagh clearly formed below the water table and almost certainly some distance inland, an environment very different to its present situation. Invasion by the sea has allowed the passage walls at its seaward end to be colonised by endolithic algae but, since light can enter only where the passage has been breached, the resultant pinnacles all point towards the opening as photokarren.

5. Pol na Grianloch (Quartz Pebble Cave):

Less than 100 metres north of Poulisallagh Bay an impressive boulder-floored trench cuts inland for about 20 metres from the cliff edge. This clearly is an unroofed section of cave passage, with a remnant of the roof overhanging the south side of the trench at its seaward end and several metres of roofed cave passage still present at its landward end. At the western end of this roofed section prominent paragenetic notches dip eastwards at an angle of $\sim 20^\circ$. Storms have long since removed any sediments that may have been present in the unroofed section of passage, but the roofed section at the landward end contains remnants of sediment deposits that must once have almost entirely filled the passage. These sediments, which contain an abundance of exotic lithologies and constitute the main interest of the site, form a series of subhorizontal units seemingly unrelated to the inclined paragenetic features preserved on the cave walls. This indicates that they are not the original sediments associated with formation of the passage itself but were emplaced at some later date after the original sediments had been partly or wholly removed.

In this south-western corner of the Burren only three main lithologies occur locally in situ and hence might be expected to contribute to any sediment accumulations within cave passages. Most abundant is grey micritic and/or bioclastic Carboniferous limestone. Within the upper part of the limestone sequence chert bands and nodules are common and hence may form a minor component of sediment deposits. The limestone is overlain by Namurian mudstones and sandstones which crop out on Slieve Elva to the east and down dip to the south. The mudstones themselves are relatively soft but they do contain much harder spheroidal or discoidal nodules of carbonate or ironstone. The sandstones are grey to brown, often weathering pale brown. There are very few mineral veins on the Burren and most of these are dominated by calcite; quartz is virtually unknown as a constituent mineral of the Burren.

Within this context the sediments preserved within this cave passage are remarkable, being overwhelmingly dominated by quartz pebbles. At least four distinct sediment units can be identified within the cave (Simms, 2000), with the uppermost of these showing strong evidence for disturbance and contamination by intrusion of limestone-rich glacial diamictite from above, presumably via now concealed openings in the cave roof a little further east. Despite significant contamination by locally derived material, the uppermost unit still contains almost

25% of exotic lithologies, including quartz, granite and schist. The two lower units are undisturbed and clearly water lain. Their composition is quite remarkable, with more than 60% of exotic lithologies in Bed 1 and more than 75% in Bed 2. Although clasts are predominantly coarse sand to granule grade, well-rounded pebbles 30mm or more across are not uncommon while a rounded half-metre boulder of granite lies among the limestone boulders at the western end of the passage. Similar assemblages have been identified in the Fergus River Cave, some 20km to the east-south-east and at several other sites (Simms, 2000). The polymictic composition of these sediments is quite unlike what might be encountered in situ locally, and also is very different from glacial tills found on the surface of the Burren today. The latter are dominated overwhelmingly by limestone debris, or by Namurian mudstones and sandstones where these outcrop locally, and glacial striations beneath indicate ice flow from the north-east. Exotic lithologies, including granite boulders a metre or more across, do occur within these surface till deposits or as isolated erratics but they are rare (Simms, 2000).

The compositional diversity of the exotic lithological assemblage found in this cave points to an origin from the north, or more probably north-west, in the granite and metamorphic terrains of the north side of Galway Bay and northwards into Connemara. It is inconceivable that these exotic clasts were fluvially transported across Galway Bay, a distance of more than 50 km for some. Instead it indicates substantial ice movement from the north-west at some time prior to the last, north-easterly, glacial advance. However, the sediments found within the cave clearly were fluvially deposited, suggesting that they were reworked from quartz-rich till emplaced onto the Burren by this earlier ice advance. Surface evidence of this till was almost completely erased by subsequent ice advance(s) but the reworked sediments washed into this cave, and others across the region, were largely protected from events on the surface.

The age of the quartz-rich sediments cannot be determined directly at this site, but the simplest scenario would have emplacement of quartz-rich till from the north-west during Oxygen Isotope Stage (OS) 4, fluvial reworking of sediment from this till into caves during the interstadial of OS 3, followed by emplacement of limestone-rich till from the north-east during the final ice advance of OS 2.

Site 1.4b. South side of Poulisallagh Bay

(Starting point grid reference M 085016)

Glacially rounded limestone outcrops are present on the south side of the bay, passing eastwards beneath a largely vegetated cover of till. Towards the sea this till cover has been stripped by marine erosion. Recently exhumed surfaces still retain glacial striations which show a prevailing north-east to south-west orientation, but karst dissolution has erased these from surfaces more than a few metres beyond the present margin of the till. Some of these striated surfaces are

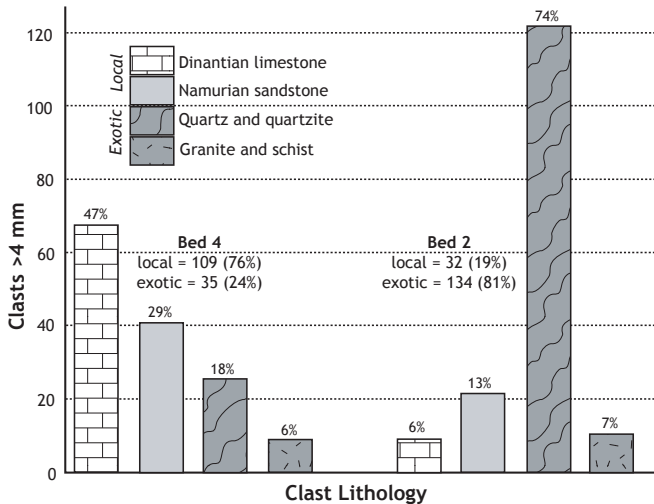


Figure 1.4.4. Frequency histogram of clast lithologies within two discrete sedimentary units in Pol na Grianloch (Quartz Pebble Cave). Bed 4, at the top of the measured succession, is disturbed and appears to have been intruded by later glacial till rich in limestone debris. For comparison, glacial till overlying striated pavement on the south side of Poulisallagh Bay contains >98% local limestone clasts with quartz clasts amounting to <1%.

backed by good exposures through a metre or more of the overlying till. Passing from east to west along this relatively small exposure a transition can be seen from in situ limestone, through slightly displaced bedrock rafts, limestone breccia, and finally to a mature till dominated by silt-sized matrix supporting mostly small, often rounded, limestone fragments. This is very similar, though on a smaller scale, to that described by Croot and Sims (1996) at Murroogh 10 km further along the coast to the north-east. The mature till at Poulisallagh, as at Fanore and elsewhere on the Burren, is dominated overwhelmingly by limestone debris. Small white quartz pebbles occur only occasionally, contrasting conspicuously with the pale to dark grey diamict. Warren (in Warren and O'Connell, 1993) noted that although such exotic clasts are present in Burren tills they do not generally show in counts of 200-400 clasts.

The glacially rounded limestone outcrop on the south side of Poulisallagh Bay is cut by a prominent parallel-sided fissure, about half a metre wide and at least three metres deep, orientated almost north-south. The fissure is choked with glacial diamict and clearly predates at least the last glacial advance. Its exact nature is difficult to discern, but it probably represents a joint-guided cave passage subsequently unroofed by glacial erosion. The uppermost metre or so of the fissure

is filled by grey limestone-rich diamict indistinguishable from that which lies on the striated limestone surface above, and in which exotic lithologies are rare. Lower in the fissure a quite distinct diamict can be recognised in which clasts, up to cobble grade, of quartz, granite and sandstone are common. Limestone still constitutes a significant component of this lower diamict, but the exotic lithologies indicate emplacement by ice movement from Connemara to the north-west. The presence of these exotic lithologies is consistent with this diamict being a preserved remnant of a once much more extensive quartz-rich till from which the exotic clasts in Pol na Grianloch were derived. The lower proportion of limestone clasts in the latter sediments, compared with this diamict, may reflect the effects of size sorting and selective removal of limestone by dissolution during a fluvial episode of reworking.

The evidence for two distinct diamicts at this site certainly supports the suggestion that the most recent ice advance across the Burren, from the north-east, was preceded by another from the north-west. This was suggested by Farrington (1965), based on the lithology and distribution of erratics, and also by Jessen et al. (1959), based on clast orientations indicating WNW-ESE ice movement in the lower till overlying the type Gortian at Boleyneendorish, but there was no way they could determine the date of this earlier ice advance. However, the fissure described here offers a unique opportunity to constrain radiometrically the dates of these events. Remarkably a 1-2 cm thick layer of flowstone (a form of reprecipitated calcite commonly found on cave walls) coats the east wall of the fissure in places and lies stratigraphically beneath the quartz-rich diamict. The age of flowstone such as this can be determined by uranium-series dating, providing a minimum age for the fissure and a maximum date for emplacement of the quartz-rich diamict. Still more remarkably, a second distinct layer of flowstone partially separates the lower, quartz-rich, diamict from the upper limestone-rich one and hence can provide both a minimum age for the lower diamict and a maximum age for the upper one. Preliminary U-Th dates obtained from these flowstones, by Mabs Gilmour at the Open University, indicate uncorrected dates of ~53 ka for the lower flowstone and ~38 ka for the upper flowstone.

These dates, if correct, are highly significant for interpreting the Pleistocene history of the region. In particular they indicate two distinct ice advances across the Burren within the last 55 ka, and hence entirely within Oxygen Isotope Stage 2. The first of these, from the north-west, occurred no earlier than ~53ka and no later than ~38ka. The presence of the upper flowstone itself suggests a brief interstadial at around 38 ka, and this may also have been when the quartz-rich sediments preserved in Pol na Grianloch and other Burren caves were emplaced, although without any additional evidence the age of these reworked sediments must remain conjectural. The age of the upper flowstone establishes quite convincingly that the most recent glacial advance across the region, from the north-east, must have



Figure 1.4.5. View of part of the south side of Poulsallagh Bay showing glacially rounded limestone overlain by bedrock rafts (left) and mature till (right). The fissure containing the dated flowstone and associated diamicts is directly below the boulder on which the person is seated.

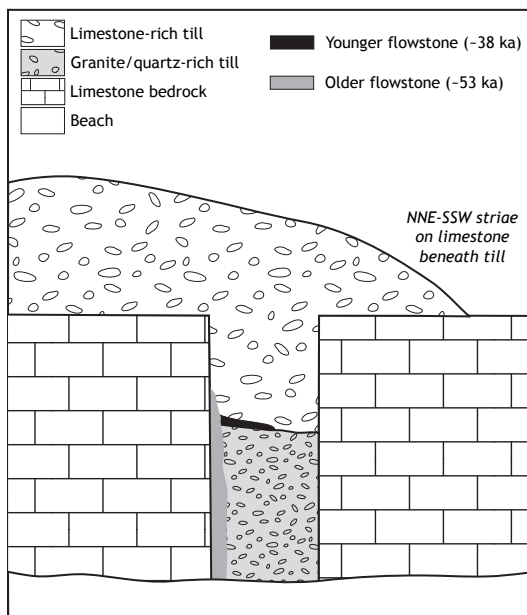


Figure 1.4.6. Diagrammatic sketch section to show the relationship of the fissure fills to the dated flowstone layers and overlying glacial till.

commenced less than 38ka ago. In general flowstone deposition is curtailed by intense cold since downward percolation of water along fractures is prevented by permafrost. Hence the presence of flowstone can be interpreted as evidence for a milder climate. The date obtained from the upper flowstone shows a remarkably good correlation with a pronounced warming identified in the GISP2 ice core between ~38-36ka (Grootes and Stuiver, 1997). Ice core correlation with the lower flowstone is less good although the date does correspond broadly with the Upton Warren Interstadial. The evidence from the tills at Poulsallagh Bay, in terms both of timing and source, supports the contention of Bowen et al. (2002) that the British and Irish Ice Sheet was mobile and sensitive to minor climatic change during the Middle and Late Devensian. The scarcity across the Burren of any surface evidence, other than occasional granite erratics, for all but the most recent (post-38 ka) glacial advance is striking and demonstrates all too clearly the difficulties of investigating the glacial history of the region.

Sites 1.5a-c. Tills, dunes and relict karst at Fanore.

(Parking grid reference M 138082)

Site 1.6. Till Section at Murrough

Michael Philcox

(Grid reference M 135093)

Croot & Sims (1996) mapped several SW-trending drumlinoid ridges <2 km long and 20 metres thick, separated by extensive areas of bare rock, in the down-ice lee of Gleninagh Mountain. One of the ridges is well exposed in cross-section in the 15 metre high coastal cliff at Murrough.

At Murrough nearly horizontal limestone bedrock is overlain by glaciotectionic rafts of local rock up to 3 metres thick and 180 metres long. These rafts are underlain by a thin (<3 cm thick) basal breccia and laterally become disaggregated into breccia. Both rafts and breccia are overlain by a lower diamict <10 metres thick with very angular clasts. This is succeeded by an upper diamict <8 metres thick characterised by a higher proportion of matrix and clasts that are more rounded, faceted and striated. Both diamicts lack sandstone or other exotic clasts. Croot and Sims (1996) analysed samples of the breccia and of the diamicts for particle parameters such as size, shape and sorting. The breccias consist of ~50% gravel-sized clasts and 50% sand and silt. The lower diamict comprises 50-70% gravel, of which 20-100% is of very angular clasts, in a sandy silt matrix. The upper diamict consists of roughly one-third gravel, with clasts commonly sub-angular, one third silt and one third sand; i.e. it has more silt and fewer and less angular clasts, and hence may be regarded as more mature. The particle-size distribution was plotted on Rosin's Law Probability graphs for comparison with an experimentally-derived ideal curve indicating an origin by crushing of parent rock. The breccia has the closest match to the ideal curve, followed by the lower

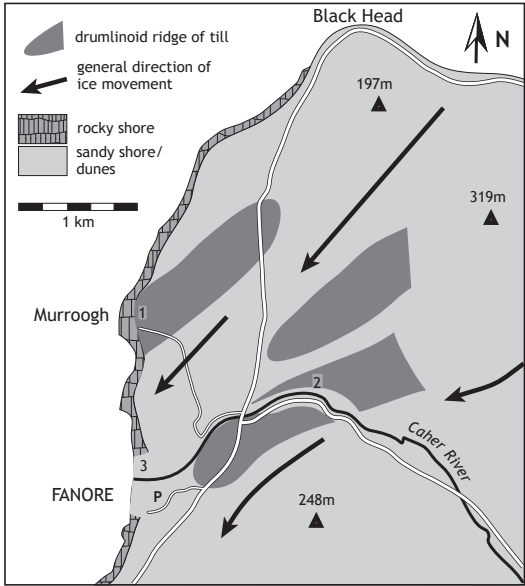


Figure 1.6.1. Sketch map of the north-west Burren coast showing the main landscape features (after Croot and Simms, 1996); 1= till section at Murrough (described by Croot and Sims); 2=till section in bank of the Caher River at the 'Khyber Pass'; 3=dune system and beach sands with relict karst beneath.

diamict (immature till), while the upper diamict (mature till) fits more closely to a log-normal curve. Croot and Sims (1996) interpreted these results as evidence that crushing is responsible for the production of the matrix in the breccia and lower diamict, whereas the matrix of the upper diamict was formed by inter-particle abrasion. At this site, therefore, the till appears to have been derived from bedrock, initially as rafts, which became progressively broken up by crushing under the weight of ice, and then modified by abrasion during transport. The lower diamict is variable in character and represents a transitional state between breccia and mature till. As silt is regarded as the terminal product of the comminution of limestone, even the upper diamict here is not fully mature.

The significance of this site derives from the monomictic composition of the various units and underlying bedrock, with only one lithology involved in the formation of the overlying till. The tills here are almost exclusively of limestone and lack exotic clasts, which elsewhere are usually common and indicate a remote source for at list some of the material. However, this site raises a pertinent question: how can a glaciotectionic breccia be distinguished from a monomict till? At Murrough the breccia below the rafts probably was never in direct contact with glacier ice, contrasting with some or all of the breccia representing disaggregated rafts. Croot and Sims (1996) suggest breccia and till can be distinguished using the closeness of fit of particle size distribution to the ideal Rosin curve. Clearly, this is not a field criterion!

Site 1.7. The Khyber Pass, Caher River

(Grid reference M 150092)

The Caher River, almost the only near-permanent surface water course on the limestone of the Burren, flows north and then north-west along a broad valley between Slieve Elva to the west and Poulacapple-Gleninagh Mountain to the east before passing through a narrow steep-sided gorge, the Khyber Pass (M 152091), to emerge onto the low coastal strip at Fanore. At its narrowest point the south flank of the Khyber Pass rises smoothly and steeply, rounded by the south-westward passage of ice but the north side comprises an extensive drumlinoid ridge of till stretching north-eastwards for several hundred metres to a glacially plucked crag. This clearly once filled the downstream end of the Caher Valley, demonstrating that the valley must predate at least the last glacial advance, but the Caher River has since carved a route through the till ridge and, in so doing, created an excellent exposure several hundred metres long and up to ten metres high. No detailed work has been undertaken at this section but it broadly resembles other drumlins in the region described by Warren (in Warren and O'Connell, 1993). It appears to be a fairly mature till, very pale and fine-grained with scattered clasts of darker limestone. In places irregular subhorizontal lines of boulders probably represent boulder pavements marking the tops of individual depositional units and indicative of lodgement till.

Site 1.8. Fanore dunes and relict karst

(Grid reference M 137085)

An extensive dune system, fronted by a sandy beach, extends to the north and a little to the south of the mouth of the Caher River (from M 137080 to about M 137094), although little appears to have been published on the site. An interesting relict karst exists beneath the sand and can be seen in the floor of some of the deepest inter-dune hollows. The sand is commonly cemented towards the base of the dunes and, in places, fills shallow grikes developed on the limestone pavement beneath. Weakly developed limestone pavement is occasionally seen when sand, which typically covers the limestone to a depth of 0.5-1 metres, has been stripped from the beach by storms. One such event even uncovered a limestone boulder atop a low pedestal, much like those still visible on the surface at Poulsallagh. Both the shallow grikes, and particularly the pedestal, testify to significant dissolution of the limestone surface for several thousand years here prior to burial beneath the dunes and beach. As such they indicate that the dune system has probably developed here only since the mid-Holocene.



Figure 1.8.1. Limestone erratic boulder perched on a pedestal in the intertidal zone at Fanore, evidence for early Holocene relict karst buried by sand. Only the top of the boulder, indicated by the attached mussels, is normally exposed above the sand.